ANALYSIS OF THE HYDROLOGIC, HYDRAULIC AND GEOMORPHIC ATTRIBUTES OF THE YOSEMITE VALLEY FLOOD: JANUARY 1-3, 1997

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Technical Report NPS/NRWRD/NRTR-97/129

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TABLE OF CONTENTS

LIST OF FIGURES

ANALYSIS OF THE HYDROLOGIC, HYDRAULIC AND GEOMORPHIC ATTRIBUTES OF THE YOSEMITE VALLEY FLOOD: JANUARY 1-3, 1997

Abstract

A flood on January 1-3, 1997, in Yosemite National Park was the largest flood in over an 80-year period of record on the Merced River. Standing water backed up in the central area of Yosemite Valley and inundated park offices, roads, concessionaire lodging units and employee housing, and other developments under as much as 8 feet of water. Downstream from El Capitan Moraine to the town of El Portal the river flowed with great force and caused severe damage to the road and sewer line connecting the Yosemite Valley with El Portal. In upper reaches of the valley, the river also had considerable energy and caused damage to campgrounds, roads and concessionaire housing units. In upper Yosemite Valley, numerous large trees along the streambanks were undercut and fell into the river. Otherwise, natural resource responses to the flood were minimal and very subtle, except where there were interactions with infrastructure. While much of the park's damaged infrastructure will be repaired, the flood provides the opportunity to remove or relocate other developments where such action would be consistent with the park's approved 1980 General Management Plan (GMP) and draft "Valley Implementation Plan (VIP)." The GMP provides direction for future planning in Yosemite and the draft VIP presents alternatives for achieving GMP goals in Yosemite Valley. The preferred alternative in the VIP has a strong orientation towards restoration of the Merced River and its riparian zone, and is consistent with effective floodplain management. This report describes the hydrologic and hydraulic characteristics of the flood in Yosemite Valley and downstream to the town of El Portal, discusses the geomorphic responses of the valley and river channel to the flood, and identifies implications for park planning and the repair of park infrastructure affected by the flood at selected sites within the park.

ANALYSIS OF THE HYDROLOGIC, HYDRAULIC AND GEOMORPHIC ATTRIBUTES OF THE YOSEMITE VALLEY FLOOD: JANUARY 1-3, 1997

INTRODUCTION

On January 1-3, 1997, the largest flood in the 80-year period of stream gage record occurred on the Merced River in Yosemite National Park. The flood resulted when a series of tropical storms dropped over ten inches of rain from December 29 to January 3 (measured at the 4000 foot level). The snowline rose progressively late in the storm series and eventually extended up to an elevation of about 11,000 feet. This rain fell on an extremely heavy early winter snowpack which extended to an unusually low elevation.

Floods are natural events in river environments and typically result in beneficial "ecological disturbance" to channel and riparian resources. Flood benefits to river resources usually stem from the processes of erosion, sediment transport, sediment deposition, and organic debris transport and deposition. However, where human infrastructure occupies flood-prone areas, adverse impacts both to infrastructure and natural resources can occur.

The purposes of this report are to:

1. Describe the hydrologic and hydraulic characteristics of the flood in Yosemite Valley and downstream to the town of El Portal;
2. Discuss the geomorphic responses of the valley and river channel to the flood; and
3. Identify implications for park planning and the repair of park infrastructure affected by the flood.

HYDROLOGIC CHARACTERISTICS: MAGNITUDE AND FREQUENCY

Flood discharges were measured at two U.S. Geological Survey (USGS) stream gages on the Merced River within the park. The Happy Isles stream gage (USGS Number 11264500) is located at the upper end of Yosemite Valley, upstream from the confluence with Tenaya Creek (Figure 1). The Pohono stream gage (USGS Number 11266500) is located at the lower end of the valley immediately upstream from the Pohono Bridge. The Happy Isles gage has been in operation since 1916 and the Pohono gage since 1917 providing about 80 years of record for each.

A peak stage of 13.24 feet was measured at the Happy Isles stream gage. This exceeded the previous high stage of 12.73 feet measured in December 1955. By extrapolating the rating curve at the Happy Isles stream gage, the USGS estimates that a peak discharge of 10,100 cfs occurred at 8:30 pm on January 2. This discharge exceeded the previous peak discharge of record which occurred in 1955 by 240 cfs. A log-Pearson Type III frequency distribution fitted to the annual peak flow series (1916 - 1996) indicates that a flood of the magnitude recorded on January 2 has about a one percent chance of occurring in any year (100-year flood). The estimated flood frequency relationship for this gage derived from the log-Pearson analysis is shown in Figure 2. At this time, both the discharge estimate and the recurrence interval should be considered preliminary estimates subject to change when the USGS has an opportunity to incorporate more information into their estimates. The maximum stage, date and time of peak, however, are considered accurate at this time due to indications that the gage continued to operate throughout the flood.

The peak stage at the Pohono stream gage exceeded the height of the stream gage stilling well and was not measured directly; however, it was accurately estimated from the high-water mark on the gage house. A peak stage of 23.45 feet was estimated at the Pohono stream gage. This exceeded the previous high stage of 21.52 feet measured in the 1955 flood. By extrapolating the rating curve at the Pohono stream gage, the USGS estimates the peak discharge to have been 24,600 cfs. The time of the peak is unknown due to the malfunction of the stage recorder but is believed to have occurred late on January 2 or early on the 3rd. This discharge exceeded the previous peak discharge of record which occurred in 1955 by 1200 cfs. It is possible that by extrapolating the rating curve at the Pohono stream gage, the peak discharge was underestimated because the rating curve was developed for flows which went under Pohono Bridge, and the extrapolation did not account for the fact that, in this flood, some flows went around and over the bridge.

A log-Pearson Type III frequency distribution was fitted to the annual peak series at the Pohono stream gage for the record from 1917 to 1996. Based upon this analysis, a flood of the magnitude experienced on January 2 or 3, 1997, is estimated to be slightly larger than the one-percent-chance-flood (100-year flood) for the Merced River at Pohono Bridge. The estimated flood frequency relationship for this gage derived from the log-Pearson analysis is shown in Figure 3.

Although the January, 1997 flood on the Merced River in Yosemite National Park was the largest on record, it was only slightly larger than the flood of 1955. Thus, roughly two floods of comparable magnitude have occurred over the past 42 years, and floods of similar or greater magnitude can be expected to occur in the future. A 100-year flood has a one percent chance of occurring in any single year. However, that same 100-year flood has about a 39 percent chance of occurring over a 50 year period, and about a 63 percent chance of occurring over a 100 year period. While the January, 1997 flood was a large flood, it is not an unusual flood when viewed within the context of the 80-year period of record.

HYDRAULIC CHARACTERISTICS: DEPTHS AND VELOCITIES

The extent of flood inundation was marked by Yosemite National Park staff. Global positioning instruments were used to geo-reference the maximum extent of inundation so that it could be depicted on valley maps (Figure 1). To understand why different portions of the river and park infrastructure were affected differently by the flood, it is useful to divide the river into five geomorphically similar reaches (Figure 4). This section describes the primary geomorphic characteristics associated with each reach, the predominant types of infrastructure found in each reach, the general hydraulic conditions experienced during the flood event and the resultant general effects. Reach 1 extends upstream from the town of El Portal to the diversion dam located at the junction of the El Portal Road (Highway 140) and the Big Oak Flat Road. Reach 2 extends from this point up to El Capitan Moraine. Reach 3 extends upstream from El Capitan Moraine to Housekeeping Camp located upstream from Sentinel Bridge. Reach 4 extends from Housekeeping Camp upstream to above the confluence with Tenaya Creek. Reach 5 includes steep, narrow reaches of Tenaya Creek and the upper Merced River.

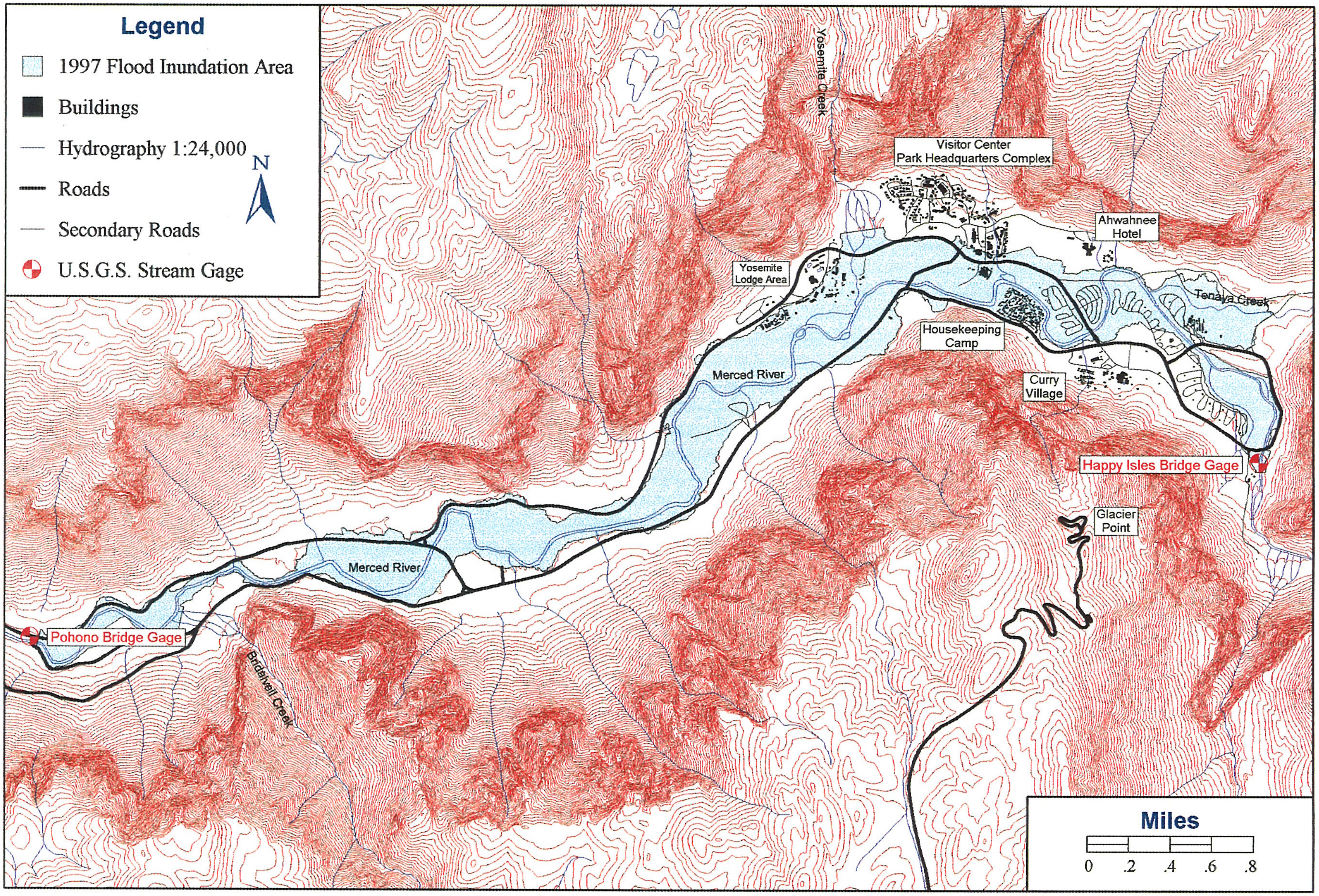

FIGURE 1. MAP OF YOSEMITE VALLEY SHOWING THE LOCATIONS OF THE HAPPY ISLES AND POHONO STREAMGAGES AND THE APPROXIMATE 1997 FLOOD INUNDATION AREA.

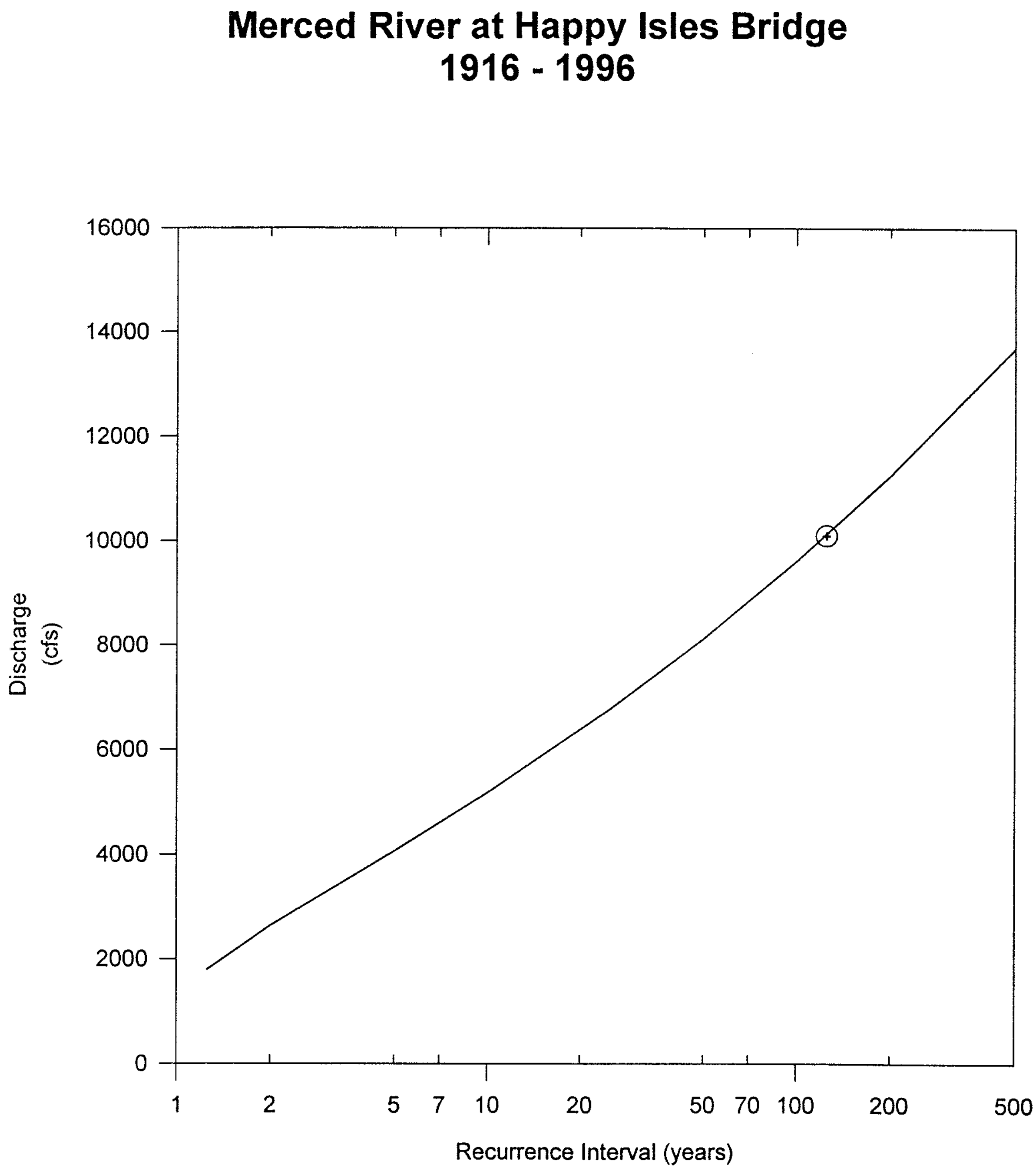

Figure 2. Flood frequency relationship for Merced River at Happy Isles Bridge stream gage, showing magnitude of the January 1997 flood. Frequency curves computed by log-Pearson III analysis of annual peak flow series for period of record (exclusive of 1997) .

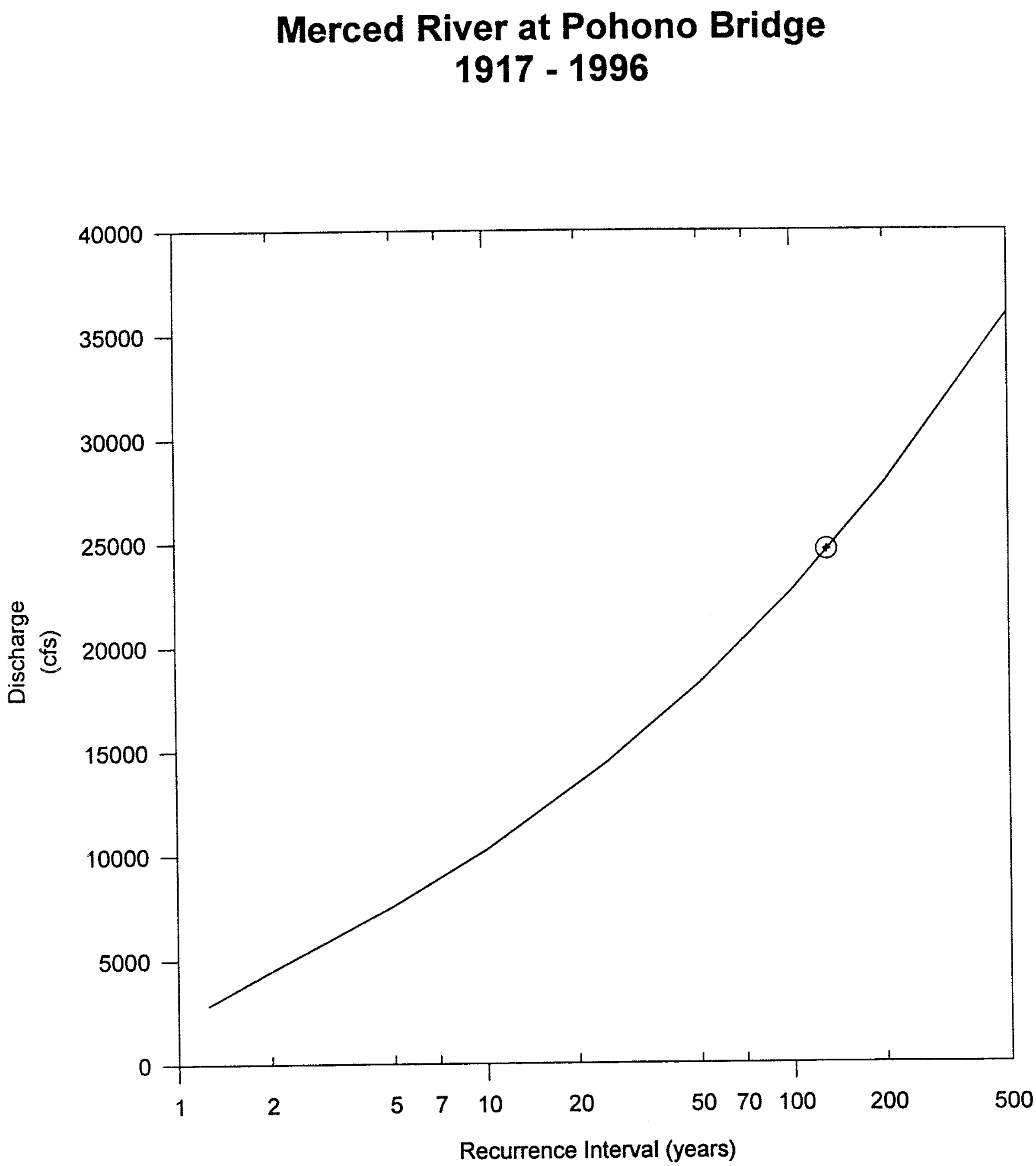

Figure 3. Flood frequency relationship for Merced River at Pohono Bridge stream gage, showing magnitude of the January 1997 flood. Frequency curves computed by log-Pearson III analysis of annual peak flow series for period of record (exclusive of 1997).

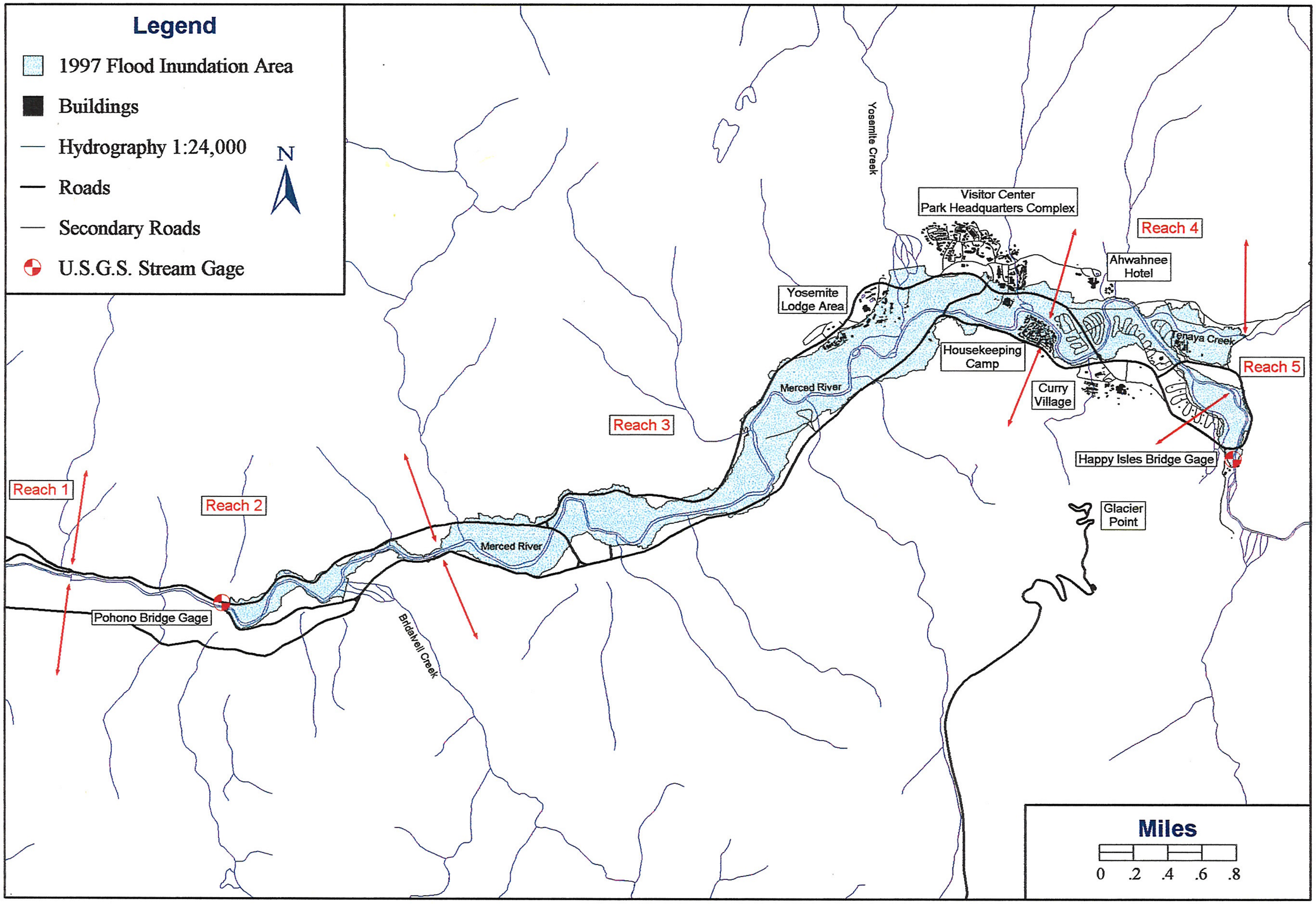

FIGURE 4. MAP DELINEATING FIVE GEOMORPHIC REACHES ALONG THE MERCED RIVER.

Reach 1: El Portal to Diversion Dam

The Merced River in the reach from El Portal to the diversion dam is generally straight with a steep gradient (approximately 350 feet per mile) and well confined by valley walls. The riverbed in this reach is comprised of bedrock, large boulders delivered by rockfall, and very large (boulder-size and larger) fluvial material. The primary infrastructure in this reach is the road and utility corridor (including sewage line) which extends from Yosemite Valley to El Portal. An NPS employee trailer court exists in the floodplain on the left river bank in El Portal a few hundred feet downstream of Highway 140 bridge. Also present in this reach is the main park maintenance facility and a sand quarry.

The flood in this reach was deep (15-30 feet) and generally confined by valley walls or by the road prism. Velocities were extremely high and flows were supercritical. Stream power and sediment transport energies were enormous. At some locations enough valley width existed for the pre-flood river to have established some slight sinuosity and side-channel bar deposits. During the flood, the river went straight down-valley, typically cutting off bar deposits and scouring any vegetation established on them (Figure 5). Many significant changes to channel alignment and character were made during the flood. Interestingly, very little disturbance to hillslope (non-riparian) natural resources was observed in undeveloped reaches downstream from the diversion dam.

The primary flood effects in this reach involved impacts to the road and utility corridor. This was a deep, high-energy flood. In places the flood mobilized the rock riprap placed to protect fill material used to construct the road prism. This resulted in erosion of the road prism and undermining of the road surface. In other places high-energy flows over-topped the road and flowed down the road, eroding fill material under the road surface and eventually undermining the road surface and causing it to fail and/or wash away.

Reach 2: Diversion Dam to El Capitan Moraine

This short reach of Merced River (about two miles) represents a transitional reach from the steep character downstream to the very mild slope upstream. In this reach the river has a mild grade (approximately 40 -50 feet per mile) with a tight meander pattern. The channel and overbank areas are comprised of glacial outwash deposits associated with Bridalveil Moraine, the lowest terminal moraine found in Yosemite Valley (Figure 6). This material ranges in size from fine material to boulders. Channel morphology is quite stable in this reach except where the river passes through the moraine deposits. In places the floodplain is well developed and proximate elevationally to the river. In other areas the floodplain is non-existent due to narrowing of valley walls or incision of the channel into moraine deposits.

Infrastructure in this portion of Yosemite Valley is limited to roads on both sides of the river, Pohono Bridge, and utility lines. During the flood, depths of flow were moderate (8 - 10 feet) in this area and velocities were high enough to move large bed material and erode banks. As in other areas upstream, overbank flow likely did not follow the channel alignment but rather traveled directly down valley in many locations. Significant scour and/or deposition occurred along both banks of the river as it passed over the old Bridalveil Moraine material causing instability (Figure 6). Except for some damage to Pohono Bridge and its approaches, there was only minor impact to infrastructure in this reach.

Reach 3: El Capitan Moraine to Housekeeping Camp

Extending upstream from El Capitan Moraine to the confluence of Tenaya Creek, Yosemite Valley is flat and wide with a very mild downslope gradient of approximately 6 feet per mile. The river in this reach exhibits a wide meander pattern with well developed floodplains. The river bed consists of sand, gravel and cobble materials. Most of the park infrastructure is in the reach between the moraine and Housekeeping Camp, including administrative offices, lodging, gas stations, bridges and employee housing.

El Capitan Moraine is the hydraulic control for the central chamber of Yosemite Valley. In effect, the moraine functioned as a "check dam" during the flood causing water to impound behind it. For every additional 6 feet of water depth at the moraine, the impounded water extended roughly another mile upstream in Yosemite Valley. Besides causing widespread inundation, the increased depths of flow also caused low flow velocities. Velocity is affected by depth of flow because, for a given discharge greater flow areas require less average flow velocity, and flow area is a function of both depth and width of inundation. The effect, therefore, of the impounded water behind El Capitan Moraine was not only great depths but low velocity which produced the lake-like conditions in the central chamber of the valley. Also of interest is the fact that as flow areas become smaller in the upstream direction due to lower depths and more constricting valley width, the flow velocities in the impounded reach progressively increase. In addition, there were localized areas of stronger currents within the impounded water of the central chamber. For example, there was indication of stronger current in the Merced River backwater in the vicinity of Yosemite Lodge and Residence One, likely caused by the substantial flow contribution of Yosemite Creek.

There is evidence that water depths over the river channel immediately upstream from El Capitan Moraine approached 25-30 feet. The impounded water extended up the valley to a point well upstream of Sentinel Bridge. At the peak of the flood, Yosemite Valley from El Capitan Moraine to approximately the Housekeeping Camp area was a large lake. Flood depths at El Capitan Meadow varied from about 6-8 feet at the upper portions of the meadow to 25-30 feet at the river. Up the valley, in the vicinity of Yosemite Chapel and the foot bridge to Residence One, estimates of flood depths based upon high-water markings varied from about 6-8 feet over the meadow near the park roads to approximately 15 feet at the river.

Although flood depths in the reach from El Capitan Moraine to Housekeeping Camp were generally great, for the reason given above, flood velocities were generally very low. One of the most noteworthy things about the flood in this reach is that there is so little evidence of geomorphic response. There are very few readily observable changes to the river channel, floodplain or riparian vegetation in this reach. Impacts to infrastructure stemmed primarily from inundation and rafting of unsecured floatable objects (Figure 7). For structures such as bridges and roads, there is very little consequence stemming from inundation in absence of significant velocity. It is also interesting to note that even floating trees and other large woody debris caused no significant damage to bridges because flow velocities were so low. In general and for the same reason, buildings also realized little structural damage from flowing water or debris.

Figure 5. Photo of post-flood Merced River channel in
Reach 1 near El Portal.

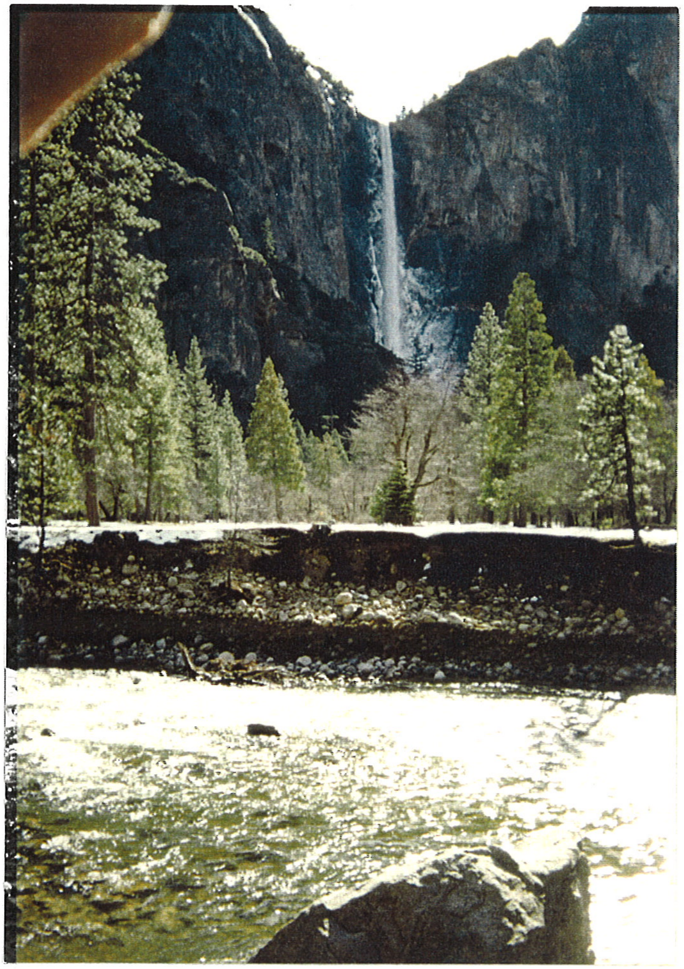

Figure 6. Photo of post-flood Merced River channel in Reach 2 where it passes over Bridalveil Moraine. Some streambank erosion is evident in this photo.

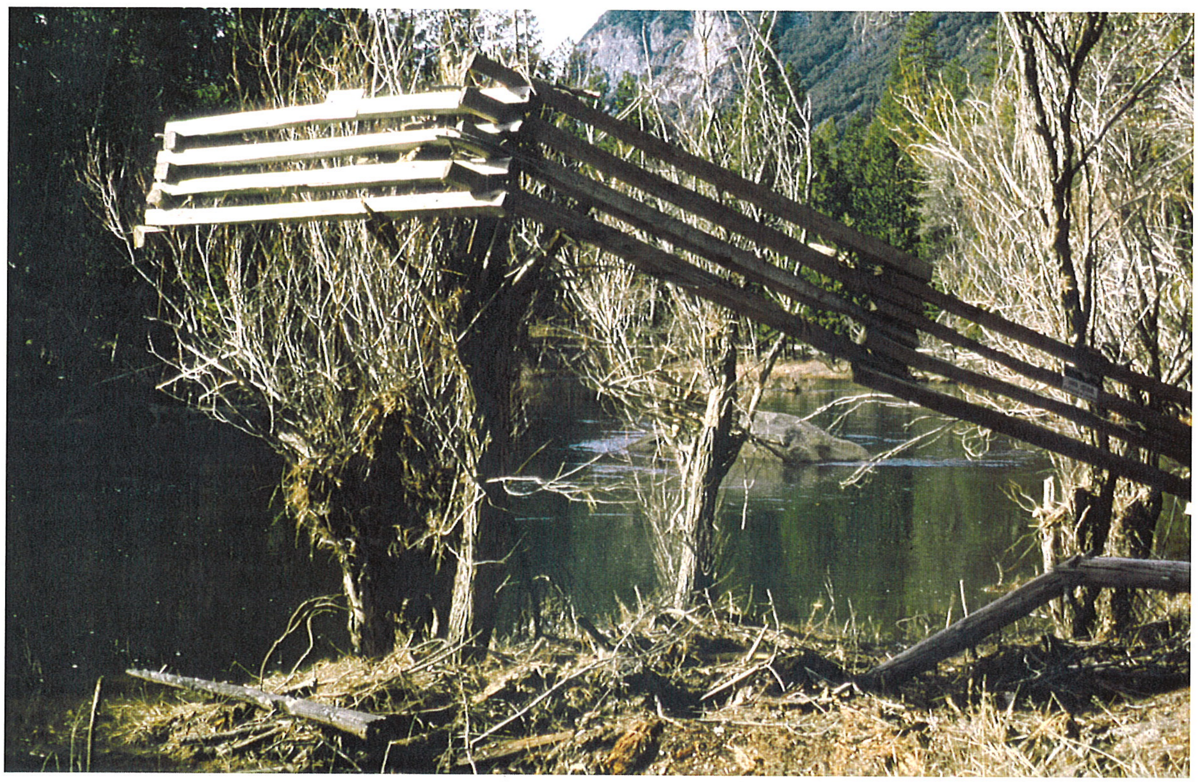

Figure 7. Photo of wooden fence, which was floated but not significantly damaged by impounded water in Reach 3 upstream from El Capitan Bridge.

Impounded water extended upstream of Sentinel Bridge. Indications are that in the vicinity of Housekeeping Camp and Lower River Campground, there was a transition from impounded to free flowing water. Water depths became more shallow and exhibited some velocity. At Housekeeping Camp, water depths approached 8 feet above the floodplain. Velocities were still low, but were sufficient to float woody debris into the lodging area. Velocities were insufficient to cause any serious structural damage to lodging units, fences or other infrastructure. The main impacts to infrastructure in this "transition" zone at the upper end of the impoundment result from inundation and deposition of woody debris against and amongst developments. Except for some localized bank erosion (which probably preceded or followed the period of peak valley inundation), there is very little evidence of disturbance to the river channel, floodplain or riparian vegetation in this reach.

Reach 4: Housekeeping Camp to Upstream from the Tenaya Creek Confluence

The Merced River from Housekeeping Camp to just upstream of the confluence of Tenaya Creek has a gradually steepening gradient and a meandering pattern. The valley floor remains fairly flat with a mild down-valley gradient. The river bed consists of sand, gravel and cobble material. The banks of the river in this reach have been heavily impacted by human use, and prior to the flood the banks were trampled, less well vegetated and more prone to erosion than banks further downstream. Furthermore, the necks of land on the inside of the river's meanders have been developed as campgrounds. Mature trees remain in the campgrounds, but there is very little understory vegetation or ground cover in these reaches. In addition to the campgrounds, infrastructure in this reach consists of roads, bridges and the Ahwahnee Hotel.

In contrast to the reach immediately downstream, the river between Housekeeping Camp and the Tenaya Creek confluence was not influenced by the water impounded behind El Capitan Moraine. Typical of meandering streams experiencing large floods, overbank flows went straight down-valley in this reach, rather than following the meandering course of the main channel (Figure 8). This resulted in out-of-bank flows cutting across the meander necks. Water depths in the campgrounds on the inside of meanders were moderate (2-4 feet) and velocities were moderate to high.

Campground developments including roads, bathrooms, picnic tables, bear boxes, and fire rings were heavily impacted, and often relocated downstream by the flowing water. In addition, water flowing across the meander necks resulted in adjustments to the river channel and floodplain. Flood channels cut across meanders, and there were areas of localized sediment deposition - both on floodplains and in channels. Also, there were areas of bank erosion, usually at the outside bends of meanders. Much of the resource adjustment which occurred was probably exaggerated by the poor condition of vegetation cover on floodplains and banks. Also, bridges, such as Sugar Pine Bridge, had inadequate capacity to convey the full flood discharge and functioned to cause additional flow to cut across meanders.

Reach 5: Steep, Narrow Reaches of Tenaya Creek and the Upper Merced River

Both Tenaya Creek and the Merced River upstream from the Tenaya Creek confluence have rapidly increasing slopes and narrowing valley widths in the upstream direction. Channel sinuosity is much lower than in the adjoining reach below. Channel beds consist of bedrock, large rockfall and boulder-sized fluvial material, particularly in the upper portions of these reaches. Banks and floodplains are vegetated with mature pines and cedars, and abundant understory. Infrastructure in this reach consists of a road up Tenaya Creek to Mirror Lake, campgrounds, a horse stable, group campground at the confluence of Tenaya Creek and Merced River, and the Curry Village lodging and housing area.

These are high-energy streams during flood events. Water is largely confined within the channel and valley walls and flows directly down-gradient. Flood flows caused minor impacts to infrastructure in this reach. A foot bridge downstream from Mirror Lake was washed out and there was erosion of the road shoulder along the road to Mirror Lake. The confluence of Tenaya Creek with the Merced River is a depositional zone. Flows during this flood concentrated their out-of-bank energies on the right side of the Tenaya Creek alluvial fan, in the area of the Group Camp. Here there was erosion of the campground and impacts to picnic tables, bear boxes, fire pits and garbage containers.

By far the most dramatic effect of the flood along the lower Tenaya Creek and the Merced River upstream from Tenaya Creek confluence involved the downing of trees and the enormous amounts of transported woody debris (Figure 9). The energies of this flood were sufficient to undermine mature trees on the river banks, causing them to fall into the river. Once in the river, trees interacted with flows to cause local areas of bed material deposition and bank erosion (and additional tree fall). Upon recession of the flood, enormous amounts of woody debris remained in the river channel and overbank areas.

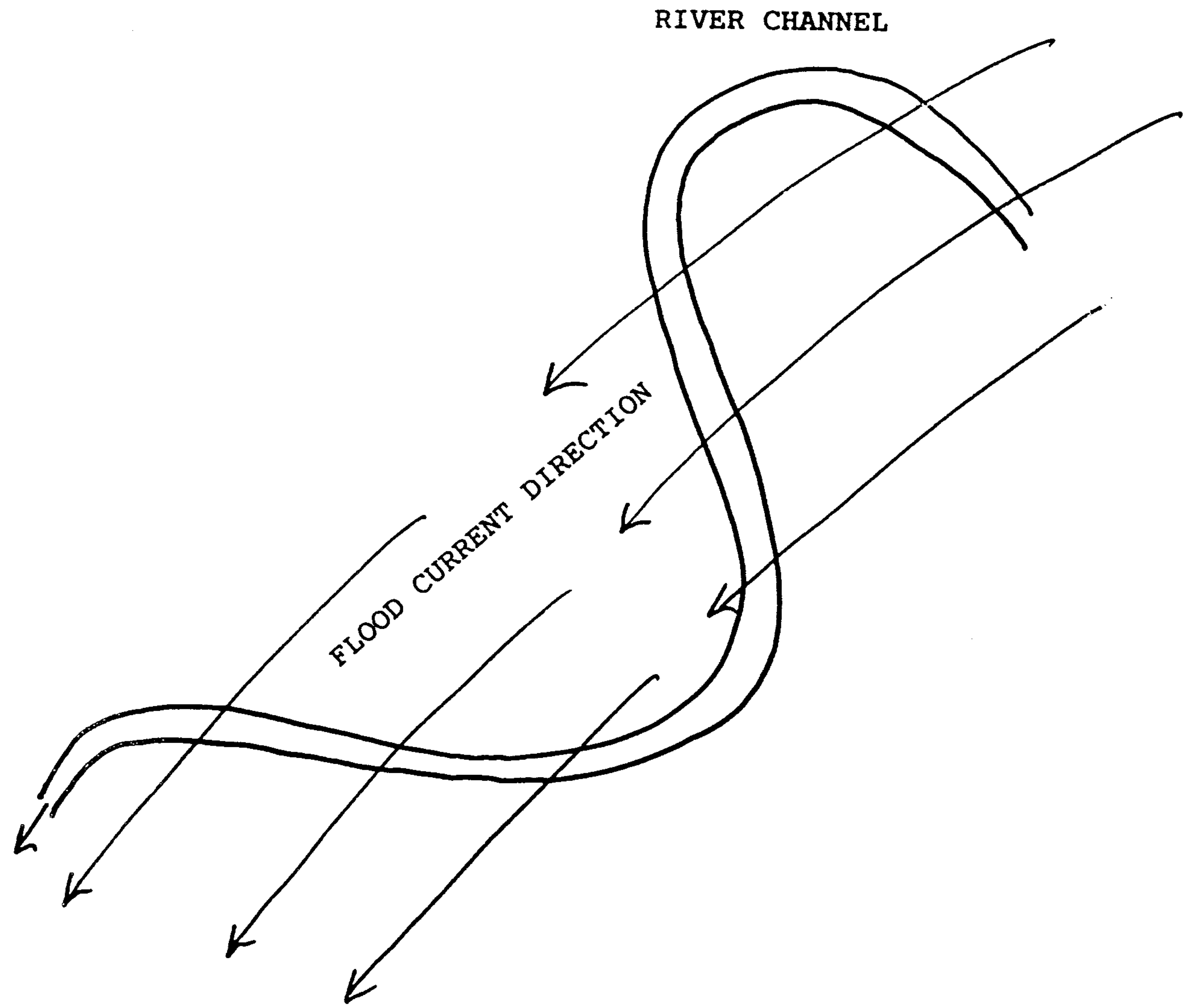

Figure 8. Sketch depicting the direction of flood flows across meanders.

Figure 9. Post-flood photo of the Tenaya Creek channel upstream from the Group Campground.

ANALYSIS OF SITE-SPECIFIC SITUATIONS

Detailed flood impact assessments were conducted for seven specific locations within the park: the El Portal area, El Portal Road at the Cookie slide and utility corridor breach, Cascades Creek Picnic Area bridge/culvert, the Northside Drive, 20 MPH Curve near Black Springs area, Lower Pines Campground, lower Tenaya Creek area including the group campground, and the Yosemite Lodge area. In the following sections, we summarize conditions and impacts experienced at these specific locations and provide some thoughts on factors to consider in planning repair and/or replacement of damaged facilities. Our suggestions attempt to be compatible with flood-related conditions as identified in the reach descriptions provided above.

El Portal Area

The El Portal area experienced more pronounced channel geomorphic response and impact to infrastructure than most other areas along the river. This is due to the extremely high energy environment associated with the steep and confined river corridor in this area. In places, the channel adjusted its alignment by cutting into adjacent hillslopes and by enlarging cutoff channels on the inside of bars. Where the road and/or utility corridor was near the river or was supported by an embankment that was within reach of the flow, substantial damage occurred.

Although much of the damage to infrastructure was experienced for the first time since construction and this event was a rare event (estimated to be about the 100-year flood), in some cases it may not be wise to simply repair/replace facilities in the prior configuration and assume that the prior level of protection would be realized. The significant channel adjustments mentioned above may cause more frequent flooding and associated damage to facilities than the prior condition. The channel adjustments may also result in the highest stream energies being focused on different reaches of streambank than before the adjustments occurred. We recommend an analysis of present channel conditions be made relative to repairs rather than assuming the risk to infrastructure has not changed.

The El Portal trailer park was protected from direct damage of the flood by the highway bridge and levee (primarily by the levee). Without these protective structures extremely hazardous hydraulic conditions would have occurred in the trailer park. The levee appears to have performed well because little structural damage is evident and the river level did not rise to a point above the levee. This is significant due to the high recurrence interval believed to be associated with this event. Additionally, the implications of the levee on river hydraulics at other locations is unlikely to be significant given the many manmade features affecting flow conditions along the river.

Although the levee withstood this and previous floods, there is the potential for overtopping by an even larger event and/or failure of the structure causing sudden, catastrophic flooding in the trailer park. For example, evidence of sapping was observed near the toe of the levee in two locations indicating the chance for structural failure. Therefore, flood risk remains an issue at this site even though little significant damage was realized during the recent flood. As directed in the NPS Floodplain Guideline, the preferred means of minimizing flood risk is avoidance of floodplains rather than structural protection. If use of this site continues in the future, we recommend that evacuation of this area be mandatory during flood events of any appreciable size.

In summary, the El Portal area is located in an extremely high energy, bed rock controlled reach with little high floodplain suitable for development. Due to high flood velocities, infrastructure and developments must be located above flood levels or be massively armored. Of note, the grouted riprap used in some locations held up well and could be used where embankment stability is crucial.

El Portal Road at the Cookie Slide and Utility Corridor Breach

The Cookie Slide area is in the same high energy reach as El Portal and, therefore, experienced the same devastating hydraulic conditions. The difference between this area and the El Portal area is that the channel is more resistant to erosion here and, therefore, less geomorphic response was realized. Also, because less infrastructure is present (only El Portal Road and utility corridor) there was less opportunity for impacts to park facilities. In several locations, the road embankment was eroded causing partial failure of the road surface. Also prevalent were zones with insufficient local drainage. Where culverts became blocked or were insufficient in number and/or size, flow in ditches parallel to the road caused widespread damage.

By far the most notable damage in this area and, for that matter, anywhere within the park proper, is the obliteration of a 300-400 foot section of El Portal Road (Figure 10). The park sewer line located under the road also was completely severed in this area. This damage was caused by the flood level exceeding the elevation of the road (by upwards of 4 feet) just upstream from a confined length of roadway. The confinement is caused by a talus slope with very large boulders bordering the road on both sides. When river flow entered the road, it traveled down the steep grade at a high velocity, tearing asphalt and road base apart and washing this material nearly completely away. This segment of road has repeatedly been damaged by high flows but nothing of this magnitude had been experienced in the past. One reason the devastation was unprecedented, besides the extremely high discharge, is that a landslide occurred in 1982 that left additional boulders along the road that lengthened the confined area and extended the amount of road length impacted by high-energy water flowing over the surface.

Several steps can be taken to improve performance of this segment of road during flood events. Two ideas proposed by Federal Highway Administration engineers include raising the road at the break-out point and blasting some of the recent landslide material to allow the flow to return more quickly to the channel. We think these are good ideas that would reduce future repair costs substantially. The amount the road is elevated can be dictated by practical considerations related to the road grade. Any additional elevation at the break-out point will not only provide a higher level of protection but reduce the amount of flow down the road when overtopping occurs. Beyond these suggestions we think that placement of more culverts and use of grouted riprap where embankment protection is deemed essential should be considered. Finally, in some cases it may be cost-effective to tolerate some level of damage from low-probability floods in some difficult locations rather than attempting to design the road to withstand extremely rare floods.

Figure 10. Photo of Cookie Slide area on El Portal Road between Yosemite Valley and El Portal.

Cascades Creek Picnic Area, Bridge, and Culvert (El Portal Road)

Cascade Creek passes under El Portal Road about one half mile upstream from the Cookie Slide. The creek upstream from the road flows through a steep, unstable rockfall area comprised of material of various sizes but primarily large boulders. Some of this material is so large that it is not reworked by fluvial processes associated with Cascade Creek. During this flood and in other large flow events in the past, the path the stream takes through this rubble field is dynamic as smaller sediments are reworked by the stream causing plugging of some channels and occupation by a portion of the flow into new channels. Thus the flow splits in a fairly random pattern and sends water down numerous channels in variable percentages. This dynamic flow character is difficult to accommodate in road crossings. At the present time, the primary opening under the road, the highway bridge, is located at a high point in the rubble field. Although the main channel was probably present at this location when the bridge was constructed, it is an unstable location and flow is easily diverted by reworked sediments to lower channels. One such lower area, located west of the bridge, contains an enlarging channel that is directed through culverts to permit water to continue downstream.

In this flood, channel changes on the rubble field have caused a large percentage of flow to travel through the culvert, even at low flow. Since culverts are easily plugged, develop large depths upstream to convey large flows, and often have erosion problems downstream, there is interest in redirecting the main flow under the bridge once again. We believe the only way to do this would be through blasting as heavy equipment probably could not access the site. Furthermore, any such attempts to keep the flow under the bridge would be successful for only a short duration because the bridge is located at a topographic high point on the debris/rubble fan, and fan geometry will remain dynamic. Perhaps the best course of action would be to allow Cascade Creek to move about as natural processes dictate and rebuild the road when necessary with a causeway or multiple bridge design. This approach, although expensive, should accommodate the dynamic nature of this stream better than the existing configuration and, if so, may be cost effective in the long-term.

Northside Drive, 20 MPH Curve near Black Springs (Yosemite Valley)

As mentioned above, this area is located in a reach of moderate slope and flood velocity. The presence of large moraine material in this area has caused the Merced River channel to be more dynamic here than in other similar locations. During this flood, the river went straight down-valley, cutting off all meander forms which existed prior to the flood. A former channel on the left bank was occupied by the flood. Additionally, flow cut off a bend on the right bank where it then flowed for several hundred feet adjacent to the road in an area which has not conveyed flow in recent times. The flow returns to the pre-flood channel over a newly-formed headcut. The exact cause of the flow cutoff along the road is not certain but it is clear that it represents a natural adjustment of the river to the high flows recently experienced.

Flows continue along the road in the location of the cutoff on the right side of the river. We do not know if base flows eventually will return to the main channel, or if the cutoff channel will continue to headcut and capture all base flows. We recommend that the park not interfere with the channel dynamics causing this new flow path but rather modify the road as needed to accommodate adjacent flow. Attempts to direct river flows would be an unnecessary intrusion on natural processes and would likely lead to additional manipulation of the river in the future to maintain the chosen flow alignment.

Lower Pines Campground

The reach associated with Lower Pines Campground behaves in a complex manner during high flows. During the January flood, this area was upstream of the inundation pool associated with El Capitan Moraine so water flowed freely here. When flood discharge was high enough to over-top the stream banks, the floodplain flow took a straighter path down-valley than the river channel which effectively reduced its length and increased its slope. Increased local slope, in turn, caused higher velocities providing more erosive power to the river. Also affecting flow dynamics in this area are Sugar Pine Bridge, Ahwahnee Bridge, and the berm across the meander point created by the road (now a bike path) prism. In addition, other preexisting factors affected the response of this reach including altered channel geometries (increased channel widths), trampled/unvegetated banks, riprap and, finally, the confluence of a large tributary, Tenaya Creek.

These factors conspired collectively to cause moderate depth but high velocity flow through much of the campground during the recent flood. While many of the park's campgrounds were damaged by the flood, none of the other sites we visited were affected as much as Lower Pines Campground (Figure 11). Flowing water rearranged everything that was not fixed in-place. In much of the campground, asphalt pavement on roads and parking spaces was peeled by the flow, broken up, and transported. The cutoff channel associated with Sugar Pine Bridge and the bike path enlarged greatly during the flood and appears to have become the primary path for flood waters through this reach. Other smaller channels were eroded further upstream in the campground above the effect of the bridge. This material was transported down-valley and some of it was redeposited on the left bank of the river downstream from Ahwahnee Bridge were overland flow velocity was reduced by high depths in the river.

At a point approximately 2/3 of the distance upstream on the meander bend, there is a rise in elevation on the meander neck. Campground units on this higher floodplain level experienced little or no flooding. All other Lower Pines Campground campsites are located low on the floodplain and will experience frequent flooding in the future.

The following discussion presents several factors to consider in planning for repair or rehabilitation of this area. First it should be recognized that much of Lower Pines Campground is in an area susceptible to damaging hydraulic conditions during floods. Conditions experienced during the January flood will be experienced periodically in the future and, therefore, investments made to rebuild camping facilities or other infrastructure in this location will continue to be subject to flood risk. Certain areas in the camp, furthest upstream, were located favorably from a flood standpoint and can be considered to be at very low-risk. Also, portions of other nearby campgrounds experienced little damage during the flood and represent the best available areas to use as camps in this part of Yosemite Valley. Much can be gained by identifying these locations and incorporating this knowledge into the decision making process.

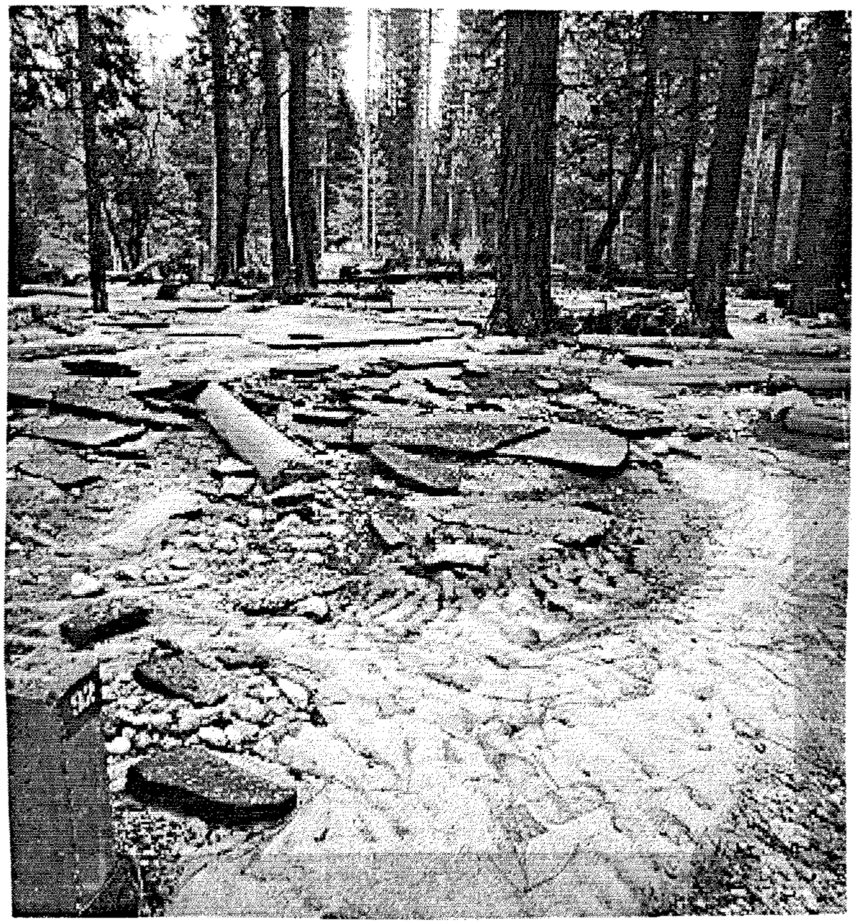

Figure 11. Post-flood photo of Lower Pines Campground.

There is the possibility that the threat of flooding may be somewhat lessened in the future by the proposed removal of Sugar Pine (and possibly Ahwahnee) Bridge(s) and the bike path prism. However, nearly all of the camp area damaged by the recent flood is naturally prone to flooding as high flows bypass river meanders, a character that will remain with or without bridges. Additionally, the large cutoff channel associated with Sugar Pine Bridge has become so large that it probably cannot be rehabilitated at this point. Therefore, significant flow will likely continue to be directed through the cutoff channel in future floods even in absence of the bridge and elevated approach road. However, significant benefit to riverine resources will result from removal of this bridge (and Ahwahnee) and removal is recommended to promote a more naturally functioning fluvial environment. Bridge removal would be beneficial to natural processes by among other factors reducing the proportion of flow entering the cutoff channel and allowing a stable bank configuration to develop on a significantly shorter time frame.

Also, related to the potential removal of Sugar Pine Bridge is the potential affect to the Ahwahnee Hotel complex. Water surface elevations will not rise across the river with bridge removal so flooding will not be more likely in this area. Additional flow down the river and into the riprapped bend between Sugar Pine and Ahwahnee Bridges could increase velocities along the outer bank of the meander; however, the outside bank is well protected and not highly susceptible to erosion.

Tenaya Creek Group Campground

Another campground facility that received significant physical damage during the flood is the Tenaya Creek Group Campground. This facility is located on the right bank of Tenaya Creek just upstream from its confluence with the Merced River. This reach is above the influence of El Capitan Moraine and, therefore, was subjected to rapidly flowing flood waters. Tenaya Creek just upstream from the camp is very steep and flows through a confined reach. During the flood, bank and hillslope failures contributed large quantities of sediment to the stream. Through the campground the creek has a lower gradient and is less confined, resulting in a depositional character. Inspection of the area lead to speculation that the creek may be slowly migrating towards the right floodplain (campground location) as a result of depositional processes.

The principal effects of the flood in this area were eroded banks with associated loss of riparian vegetation and accumulation of massive quantities of woody debris on the floodplain. The bank erosion probably was caused by a combination of natural channel migration pushing the stream in that direction and, possibly, compromised bank integrity caused by human use. The woody debris accumulated simply as a result of abundant supply of material in the river and the opportunity to lodge in the sparse timber, brush, and fixed objects in the campground.

If the notion of the channel migrating slowly to the right floodplain on what is essentially an alluvial fan is correct, the long-term use of the campground location will be problematic. Repeated destruction of facilities can be anticipated in the future by woody debris and inundation as aggradation causes lesser floods to access the overbank areas. Additionally, bank erosion will likely continue causing a loss of developed area leading to the need for bank stabilization. Artificial bank stabilization is never a desirable activity in a national park but in an aggradational environment such as this, it would not only be harmful to resource conditions but would also likely require channel manipulations such as dredging in the future. Our recommendation for this site is to invest minimally, if at all, in repairing the existing facility and consider moving the campground to a more stable location. The left overbank area of Tenaya Creek in the same reach may be a more stable location, as would be an abandoned terrace level upstream on the right bank.

Yosemite Lodge Area

As mentioned above, Yosemite Lodge is located in geomorphic reach 3, the area that was subjected to considerable depths and relatively low velocities during the January 1997 flood. Many of the lodge cabin units are located fairly close to both the Merced River and Yosemite Creek and, therefore, were subjected to substantial depth during the event.

A total of 94 cabin and cottage structures were inundated by flood depths ranging from about one foot to over eleven feet. Assuming that this event was close to the 100-year flood discharge, then any structure that flooded can be considered to be within that design floodplain. However, it was obvious from the depth of inundation that many of the structures are located in areas that can be expected to flood on a more frequent basis. Consequently, a depth-frequency relationship for the Yosemite Lodge area was established using records from historical floods.

The depths of inundation and corresponding date of four historical floods have been recorded on an inner wall of the Residence One garage. These depths were translated into an elevation relative to the 1997 event which left an almost ubiquitous high water mark in this area. Working backwards, these depths were correlated with the estimated frequency of each event recorded at the Pohono gage. With these four pairs of relative depth and recurrence interval, a linear regression was developed to predict relative depth associated with more frequent floods. The resulting coefficient of determination was 0.78 indicating a fairly strong correlation between relative depth and estimated recurrence interval.

Using this relationship, individual structures were assigned a flood frequency based on the depth of flooding during this event. When all of the structures were tabulated, approximate floodplain boundaries were drafted on a base map using lodge units and their associated flood frequency as delineation points (Figure 12). From this map it is possible to estimate the frequency that particular areas of the lodge will be flooded. However, it is important to note that not all of the structures located in the lodge area are depicted on the base map. The area most prone to flooding is the "cabin without baths" section which is not shown on the base map. This area is located roughly due south of the Laurel and Juniper Cottages and contains at least 4 units located in the approximate 2-year floodplain, an additional 13 units in the 5-year floodplain, and as many as 25 units in the 10-year floodplain. Two additional areas associated with Yosemite Lodge but used as concessionaire employee housing are the Annex Cabin area and Camp Clark. Both of these areas experienced substantial flooding during the event and should be considered flood-prone. An example of the depth of flow experienced during the January 1997 flood in this area is shown in Figure 13. Flood depths in Camp Clark were in excess of 7 feet or roughly within the 30-year floodplain. The Annex Cabin area was subjected to flood depths that ranged from 4.7 to 5.6 feet, which corresponds roughly to the 50-year floodplain.

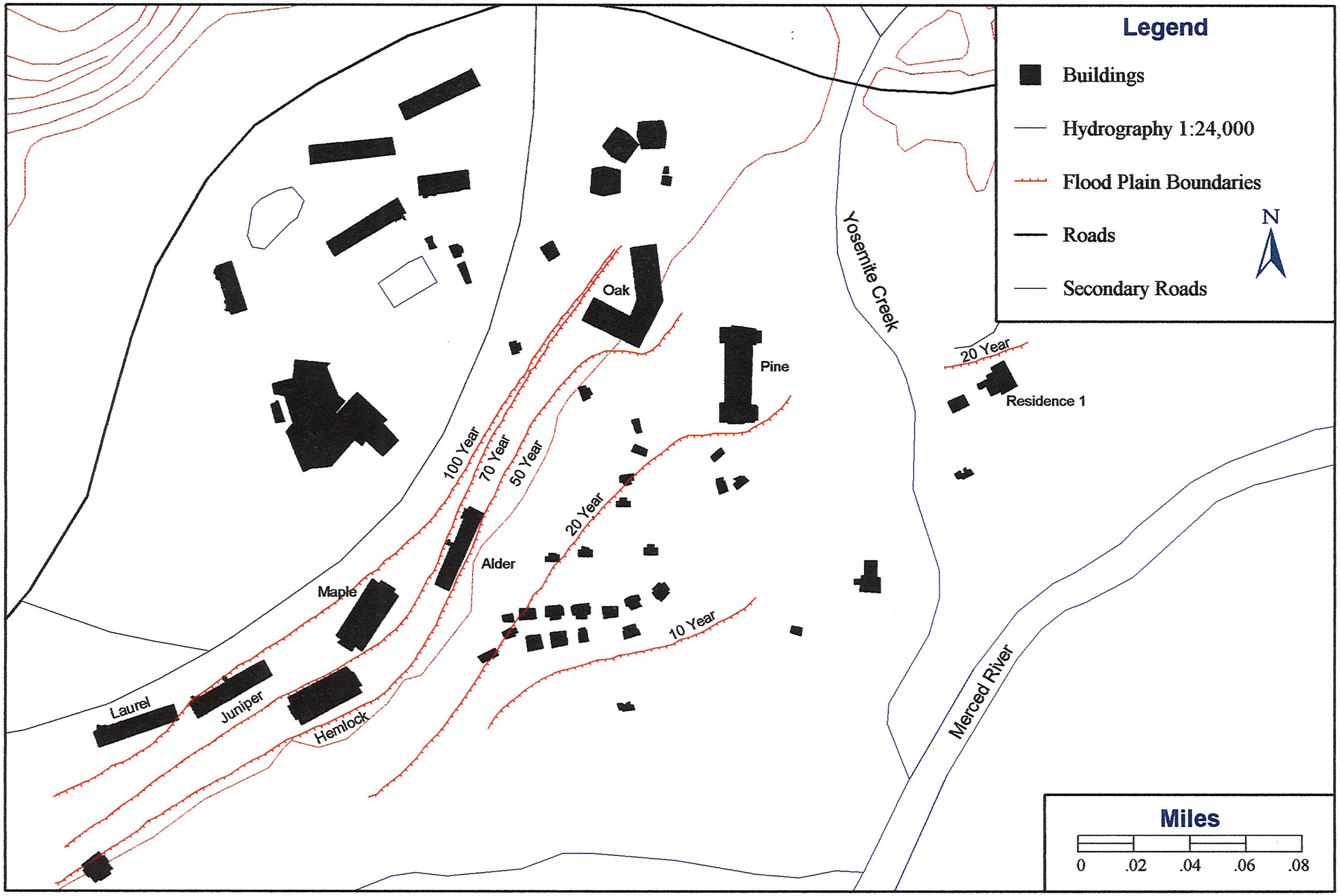

FIGURE 12. CLOSE UP MAP OF THE YOSEMITE LODGE AREA SHOWING APPROXIMATE FLOODPLAIN BOUNDARIES WITH ASSOCIATED FREQUENCIES.

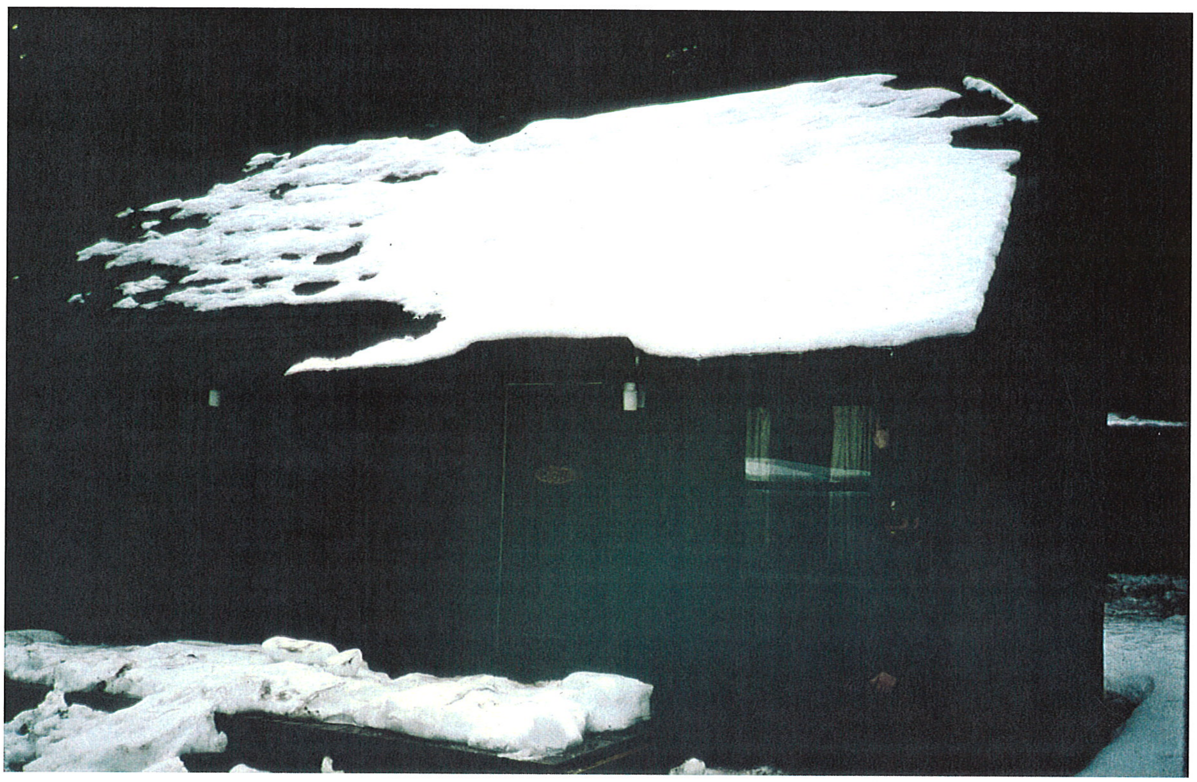

Figure 13. Photo of high-water line on Yosemite Lodge unit.

IMPLICATIONS OF THE FLOOD ON YOSEMITE VALLEY PLANNING

When viewed strictly as a natural ecosystem event, one of the most striking things about the January 1997 flood was how little it did in the way of ecosystem disturbance or natural resource adjustment. Most adverse impacts stemming from the flood were to infrastructure, and where adverse impacts to natural resources occurred it was usually the result of the interactions of flood flows and infrastructure.

Most natural resource adjustments which occurred should be viewed as natural ecosystem processes. It is important not to overreact to such things as tree fall, organic debris transport and deposition, and stream channel sedimentation and realignment. For example, where woody debris accumulation does not significantly affect the use of a site such as a picnic or campground area, it probably should not be cleaned up. Sediment and debris which accumulated in campground areas could significantly contribute to the restoration of ground cover in these areas and should be integrated, where practical, into site restoration plans. Tree fall in the upper Merced River and Tenaya Creek is part of natural channel processes and contributes to aquatic habitat diversity. These trees pose little immediate or long-term threat to downstream infrastructure. This is especially true if the park proceeds with the implementation of its General Management Plan as described in the preferred alternative of the Draft Valley Implementation Plan (VIP). This plan calls for removal of selected bridges and relocation of the most flood-prone campgrounds (see comments on the VIP, below).

Almost the entire Yosemite Valley is a natural floodplain. A useful thing about this flood is that it permits an accurate delineation of the 100-year floodplain (the floodplain criteria most often used in planning activities). This is especially useful in areas where park infrastructure is concentrated (Figure 14). It will be virtually impossible for all park infrastructure to be located outside the floodplain. The issue in Yosemite Valley is how best to occupy the floodplain in a way which minimizes impacts to park resources and the risk to infrastructure. In this regard, there are some important lessons to be learned from this flood.

The nature of flood impacts to infrastructure correlates directly with the different ways the flood expressed itself in the five reaches of the Yosemite Valley as described above. The fact that flood characteristics are so strikingly different in these different valley reaches has profound implications for the siting of park infrastructure. Structures and facilities sited on floodplains in high-energy reaches of the valley (downstream from El Capitan Moraine, and upstream from roughly the Housekeeping Camp area) are subject to destruction during high flows. Infrastructure which needs to be located in high-energy reaches should either be of low enough value to justify periodic replacement or designed in a way that it can withstand substantial hydraulic forces and large debris transport. To minimize resource impacts stemming from the interaction of flowing water and infrastructure, as much setback in the floodplain as possible is recommended.

Infrastructure in the impounded reaches of the central portion of Yosemite Valley are not subject to destruction by flowing water, but are subject to damage by inundation. In this reach, the extent of damage and the amount of resulting clean-up will stem both from the nature of the infrastructure and its relative floodplain location. The lower infrastructure is located relative to the river, the more frequently inundation will occur and the deeper will be the inundation. For example, infrastructure such as bridges, roads, and picnic facilities are essentially immune to inundation and can be successfully located closer to the river than can lodging and housing facilities. Damage to infrastructure which is vulnerable to inundation can be minimized by locating developments as high in the floodplain as possible. The higher the elevation above the river, the less will be both the frequency of inundation and the depth of inundation.

The preferred alternative in the draft Valley Implementation Plan has a strong orientation to restoring more natural conditions along the Merced River corridor. Implementation of this plan clearly will result in reduced long-term risk to park infrastructure from flooding. Proposals in the VIP to remove Ahwahnee, Sugar Pine and Stoneman Bridges are consistent with restoring natural river processes. These bridges are in high-energy reaches during floods. They are susceptible to damage from flood and large debris, and they interact with flood flows to induce unnatural channel and floodplain impacts. Downstream bridges were under impounded water and velocities were insufficient to threaten the integrity of those structures, either from flowing water or logs.

Plans in the VIP to restore all or portions of River Camps and Lower Pines Campground also are consistent with restoring natural river processes and conditions and minimizing risk to infrastructure. Both these campgrounds are on meander necks and are vulnerable to swiftly flowing flood flows cutting across them. Of the two campground sites, Lower Pines probably experiences the strongest hydraulics during floods and is most vulnerable to impact. The River Camps were in the tailwater of the lake impounded behind El Capitan Moraine. Flows here were somewhat deeper and slower than at Lower Pines.

Plans in the VIP to relocate the group camp at the confluence of Tenaya Creek again are consistent with ongoing geomorphic processes, and the river currently appears to be migrating into this area. A walk-in camp at this site may be more vulnerable to future impacts than if it were located on the left bank of the river, given the current adjustment tendencies of the river.

Plans in the VIP to remove or relocate lodging facilities which were low to the river and deeply inundated are consistent with good floodplain planning. These facilities will be frequently inundated and, on occasion, severely inundated.

In summary, the preferred alternative in the VIP is strongly oriented to effective floodplain management.

When it is necessary to occupy floodprone areas, the NPS Floodplain Management Guidelines encourage parks to have effective flood warning and evacuation plans. The Yosemite Valley flood warning system is based upon a "decision tree" approach, whereby if several questions are answered in the affirmative, valley flooding can be anticipated. These "questions" (e.g., Is the river near flood stage? Does the forecast call for more rain? Is there a heavy snowpack? Is it continuing to rain at Tuolumne Meadows?) form an excellent flood warning system. We do not think the existing park warning system could be improved by sophisticated meteorologic or hydrologic modeling.

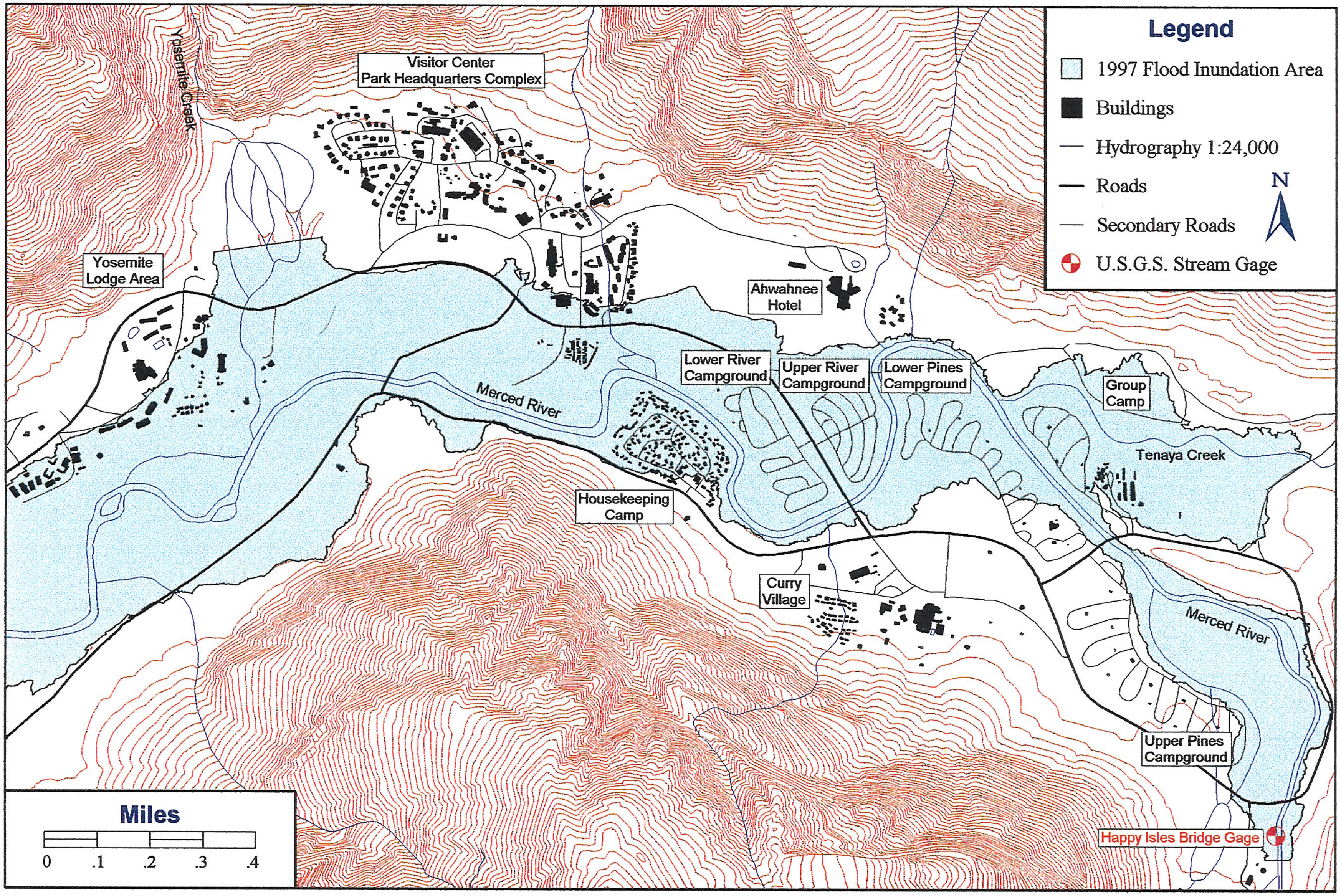

FIGURE 14. THE 100-YEAR FLOODPLAIN IN THE AREA OF CONCENTRATED PARK DEVELOPMENT, AS DETERMINED FROM THE 1997 FLOOD.

SUMMARY

The January 1-3, 1997, flood on the Merced River in Yosemite National Park was the largest flood in an 80-year period of record and very closely approximates a 100-year return-period flood. The flood had different characteristics in each of five geomorphic reaches and influenced resources and impacted infrastructure differently in each of those reaches.

Downstream from the diversion dam to El Portal, the river flowed with great force. Resource adjustments were largely confined to the reworking and redeposition of large side- and mid-channel bar deposits. Severe damage to the road and sewer pipeline occurred in this reach.

From the diversion dam upstream to El Capitan Moraine, the river is less steep and only moderately confined. Resource adjustments included some bank scour (in the vicinity of Bridalveil Moraine) and the cutting of flood channels across meander bends. There was minor impact to roads and bridges in this reach.

In the central chamber of Yosemite Valley, between El Capitan Moraine and roughly the Housekeeping Camp area, water was impounded by the moraine and was deep and very slow-moving. There was minimal resource adjustment in this reach, but a large number of park developments were submerged in deep standing water.

In the upper reaches of the valley, between Housekeeping Camp and a point upstream from the confluence of Tenaya Creek, flood waters flowed over the floodplain and across river meander necks. Infrastructure in this reach, including campgrounds and tent housing units, were heavily impacted. There was considerable scour, and sediment and organic debris deposition on floodplains and meander bends in this reach.

In the steep, upper reaches of the Merced River and Tenaya Creek, the river was confined and flowed with great force. There was bank erosion in this reach and many shoreline trees were uprooted and deposited in the channel. Some road and footbridge damage occurred in this reach.

Figure 15. Photo of large woody debris piled up against El Capitan Bridge. This debris was floated by impounded water behind El Capitan Moraine. However, because velocities were low, very little damage was done to the bridge.

As the nation's principal conservation agency, the Department of the Interior has the responsibility for most of our nationally owned public lands and natural and cultural resources. This includes fostering wise use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people. The Department also promotes the goals of the Take Pride in America campaign by encouraging stewardship and citizen responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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